Influence of shapes, contact forces and high copper alloys on the contact resistance and temperature

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Abstract: - The purpose of this paper is to present an experimental and a numerical study of simple geometries representing the electrical contact in automotive connectors (a sphere-plane and cylinder–plane electrical contact) when a current passes through them. High copper alloys were used to improve mechanical and electrical connector behaviour. Changes in the electrical contact resistance versus force in the range of 1-100N for different sizes and geometries were studied. The designed samples were subjected to indentation (static contact). Temperature variation for different high copper alloys was studied for different forces and currents. The temperature reached near the contact area, between two solids constituting the contact, is a significant parameter to indicate the damage level. However, it is very difficult to know the inner temperatures. The only way to obtain them was to use a finite element code. A finite element simulation code including the roughness contact surface profile was carried out to obtain these internal temperatures. The numerical results were in agreement with the experimental results. On the other hand, a numerical size optimization using the subproblem approximation method was carried out to obtain the resistance gain or the volume gain with mechanical, geometrical and physical constraints. Useful results were obtained to evolve compromise between the electrical and mechanical aspects for a power connector and to help manufacturers decrease weight and electrical contact resistance of their connectors.

Key-Words: - Electrical contact resistance; Temperature; Finite element; Optimization; Power connectors; Roughness surface.

1 Introduction

The increase in electronic and computer controls in transport, machining and numerous other industrial and domestic applications has induced a fantastic increase in connector applications during the last decades. The connectors for automotive applications are often subjected to harsh environmental conditions. Long term exposure to extreme levels and rapid variation, humidity and temperature deteriorate the connectors and reduce the reliability [1]. To satisfy a growing demand for electrical power in modern car generations, the 14 V battery has to be extended to 42 V. Because of the difficulties of implementing a new 42 V system, the present tendency is to increase current levels at 14 V up to 100 A. This fort current is the origin of the intense Joule heating in the contact surface of the connector and can contribute many problems which require the conception of new power connectors and decreasing of the electrical contact resistance. A minimisation study of contact resistance and temperature in the range of 10-100A was developed in the present paper for different high copper alloys with different geometries and contact forces. Though it is very difficult to simulate the exact conditions of the automobile connectors encounter in real life, it is possible to study the effect of certain conditions and to correlate their influence on the extent of temperature variation and in turn to predict the reliability of connectors.

Much work [2-8] has been devoted to understanding the contact zone mechanisms but their complexity led us to study a simple contact shape with former copper alloys. But no study has studied the influence of roughness on the changes of resistance in the contact zone for high copper alloys. In this work, different sizes and geometries (sphere-plane and cylinder–plane electrical contacts) were analyzed. Samples were subjected to different contact loads and different current values in the indentation tests. When the roughness profile is taken into account, the finite element model developed by Ansys software [9] leads to an improvement of the numerical resistance values. The temperature near the contact zone was measured for different currents and indentation forces. It was shown that the material resistivity has a non negligible influence on the temperature variation. Finally, a numerical design optimization was undertaken to obtain optimum contact resistance with several mechanical, electrical and physical constraints. To
minimize the connector weight, another design optimization was carried out when the objective function was the sample volume.

2 High copper alloys used and experimental set-up

2.1 Materials Used

The present study analyses the contact resistance evolution for high copper alloys samples Table 1.

<table>
<thead>
<tr>
<th>Copper alloy</th>
<th>Composition</th>
<th>Yield stress (MPa)</th>
<th>Thermal conductivity (W/mK)</th>
<th>Electrical resistivity (Ω.mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cub1</td>
<td>Cu 99.9% + 0.008% P</td>
<td>200</td>
<td>340</td>
<td>2.12 $10^{-5}$</td>
</tr>
<tr>
<td>C10100</td>
<td>Cu 99.99%</td>
<td>200</td>
<td>401</td>
<td>1.68 $10^{-5}$</td>
</tr>
<tr>
<td>C70250</td>
<td>CuNi3SiMg5</td>
<td>514</td>
<td>190</td>
<td>4 $10^{-5}$</td>
</tr>
<tr>
<td>C19400</td>
<td>CuFe2P</td>
<td>401</td>
<td>280</td>
<td>2.7 $10^{-5}$</td>
</tr>
<tr>
<td>C18070</td>
<td>CuCrSiTi4</td>
<td>420</td>
<td>310</td>
<td>2.2 $10^{-5}$</td>
</tr>
<tr>
<td>C19210</td>
<td>CuFeP</td>
<td>322</td>
<td>350</td>
<td>1.88 $10^{-5}$</td>
</tr>
<tr>
<td>C14415</td>
<td>CuSn0.15</td>
<td>333.5</td>
<td>350</td>
<td>1.96 $10^{-5}$</td>
</tr>
</tbody>
</table>

Table 1: Characteristics for different used copper alloys

Fig.1 shows the different behaviour laws (stress versus strain) for different copper alloys which will be used to elaborate the tested U-samples. By using these elastoplastic laws in the finite element code Ansys, one can simulate the contact surface deformation.

Before each test, the samples surfaces were cleaned by an antioxidant paste and then dipped by an ultrasonic alcohol bath. Three new samples were used in each test. The experimental measurement bench was monitored by a microcomputer over a GPIB bus and instrument. This enables a low stepping motor to be used for progressive force loading and current sourcing, contact voltage measurement and data collecting. The following test was carried out to simulate indentation phase. This test consisted in applying a progressive contact force $F_c$ : 2, 4, 8, 16, 32, 64 and 100 N (Fig.3) for measuring the contact resistance.

2.2 Experimental set-up

Since the geometry of the flat and upper specimen were relatively small, thermo-couples with high response time (J type) are used to measure the temperature variation near to the contact zone and in the extremity of the sample (Fig.4). A range of electrical current 10, 50 and 100 A was applied by a D.C. generator. A microvoltmeter (Keithley) with 1 µV resolution, was used to measure the fall of potential by the “four wire” method. Thus, the contact resistance during indentation phase could be obtained. The two samples were fixed on insulator solid piece. The contact force was imposed with the help of the vertical displacement of the upper part which was activated by a step-by-step engine with a precision of 1µm. This force was measured by a force

\[ F_c \text{ from 1 to 100N} \]

Fig.3 : Sample under indentation load (spherical or cylindrical /plane contact)
3 Finite element modelling

Simultaneously with the experimental tests, a numerical modelling is undertaken. One can suppose that the contact surface is smooth (without roughness) or one can take into account the real roughness profile in the numerical modelling.

Two finite element models are proposed with or without the contact surface roughness. The measurement of the roughness profile was obtained with the help of a profile meter. Regarding the symmetric form of the sample parts, only half part of the samples was meshed (Fig.5). Fig.5(a) and (b) give the adopted meshes for these two configurations.

Underlying the approach in this code is the discretization of the continuum involved. Also, an important feature of this program involved the ability to model the contact between the spherical or cylindrical part and the plane part as a sliding interface.

As the spherical or cylindrical part goes down during the indentation test, the software detects the nodes in contact to evaluate the contact surface.

3.1 Material behaviour

Simulation of the displacement for a symmetric model and the large deformations with elastoplastic behaviour was obtained with the Ansys finite element code. The material behaviour model used for modelling the nonlinear response of the different high copper alloys presented in Fig.1 is described by multilinear stress-strain curve (option : MISO) starting at the origin with positive stress and strain values. This option uses the Von Mises yield criteria coupled with an isotropic work plastic hardening assumption.

3.2 Indirect coupling method

The deformation of contact surface under applied contact forces and the numerical contact resistance and contact temperature values were calculated basing to the indirect coupling program. This developed program is based to the coupling with the mechanical and thermo electrical fields. Fig.6 shows the algorithm for numerical solution of the thermo-electro-mechanical problems using the indirect coupling method [10].

This method begins with the study of the mechanical behaviour using axisymmetrical eight structural solid
nodes elements (Plane183-2D) and 3 nodes surface to surface element for the contact area (Conta172) and target area (Targe169). Then the deformed structure is saved and the mechanical elements (Plane183-2D) are replaced by plane eight nodes coupled field solid elements (Plane 223- 2D) with degrees of freedom: temperature and voltage (Fig.6).

The contact algorithm used is the Augmented Lagrangian method. Contact, material and geometric non-linearities required a full Newton Raphson scheme to be used with the sparse matrix solver (direct solver). These surface-to-surface contact elements use Gauss integration points as a contact detection point. The program checked the convergence of the iterative solution by using a force criterion.

The friction coefficient $\mu$ between two surfaces in contact (copper alloy/copper alloy) was equal to 0.2. The program was used with 9 817 elements and 28 313 nodes for the model with the roughness modelling. A total of at least 708 elements were allowed to come into contact with the plane part in order to provide sufficient resolution in the computation of the field around the contact zone. Other smoothness meshes were tested. The conclusion was that the results were identical. To get better results, the contact zone was refined (Fig.5, Zoom of the contact zone).

### 3.3 Boundary conditions

In the mechanical analysis the upper surface of the spherical or cylindrical part is submitted to a pressure. Due to the symmetric configuration, the boundary conditions may be expressed as follows:

\[ U_y (y = -0.8) = U_x (y = -0.8) = 0 \]  (1)

where $y = -0.8$ (mm) denotes the lower surface of the plane part,

\[ U_x (x = 0) = 0 \]  (2)

$U_y$, $U_x$ are respectively the displacement according to $y$ and $x$ axis (Fig.5).

In the thermo-electrical analysis the upper surface of the spherical or cylindrical part is submitted to a current and temperature which has been measured by the experimental instruments. The lower surface of the plane part is submitted to temperature and zero voltage.

### 4 Results and discussion

#### 4.1 Current and force influences

The C19210 alloy presents a low resistance in comparison with the other copper alloys used. On the other hand, electrical contact resistance decreases inversely to the applied load (Fig.7) [11]. When the roughness profile is taken into account, numerical modelling leads to a good approximation to the experimental results (Fig.7 : results for cylindrical contact). The same conclusions were obtained for the other high copper alloys. For the same conditions, one can note that the experimental results when a spherical contact is used, leads to lower electrical contact resistance values (Fig.7).

![Fig.7: Contact resistance of cylindrical and spherical contact (C19210 copper alloy)](image)

The sphere/plane contact led to lower contact resistance values, which are thus more interesting for the connector manufacturers whose first concern is to minimize this resistance. Fig.8 gives for different copper alloys the temperature variation for different applied loads and different current values in the case of spherical contact. Note that the temperature (noted $\Delta T$) is the difference between the ambient laboratory air temperature (equal to 22°C) and the real temperature near the contact zone.

![Fig.8: Temperature variation for different copper alloys under spherical contact](image)

The copper alloys are classified according to the ascending electrical resistivity value (C10100 has the lowest resistivity and C70250 has the highest resistivity – Table1). Temperature increases according to the electrical resistivity of the studied material. High current...
leads to high temperatures whatever the applied force. The current is the dominating parameter which influences the increasing temperature values. The high contact forces lead to large contact zones and thus to a least temperature.

4.2. Numerical design optimization

Several connector manufacturers wish to reduce the contact resistance or the connector mass. The optimization procedure is then used. For our study, optimization means minimisation of the contact resistance or the sample volume. Traditionally, improvements in a design come from the process of starting with an initial design, performing an analysis looking at results and deciding whether or not we can improve the initial design. This procedure is shown in Fig.9. The objective function which will be optimized can be the electrical resistance or the volume of the sample.

The selected parameter designs or design variables were the sphere radius \( R \) and the sample thickness \( e \) with the following geometrical constraints:

\[
0.7 \text{mm} \leq e \leq 1.5 \text{mm} \quad (3)
\]

\[
2 \text{mm} \leq R \leq 4 \text{mm} \quad (4)
\]

Note that the initial sample thickness was equal to 0.8 mm and the initial radius was equal to 3 mm. For the optimization procedure, the selected material is the C19210 copper alloys because this material presents the minimal electrical contact resistance and the minimal temperature (Fig.8).

When the objective function was the minimisation of the electrical contact resistance, the mechanical Von Mises stress \( \sigma_{VM} \) (state variable) must be less than the yield material stress \( \sigma_Y \):

\[
\sigma_{VM} \leq \sigma_Y = 322 \text{ MPa} \quad (5)
\]

When the objective function was the minimisation of the sample volume, the electrical contact resistance \( R_C \) (state variable) must be less than the initial contact resistance \( R_{IC} \) at 10 N:

\[
R_C \leq R_{IC} = 0.12 \text{ m} \Omega \quad (6)
\]

The electrical contact resistance decreases according to the contact force \( F_c \). When the objective was the contact resistance, Fig.10 shows that the contact resistance gain \( R_C \) for a sample under a load of 10 N is equal to 8%. On the other hand, we obtain a volume increase but a decrease of the Von Mises stress which is located only in a small zone near the contact zone.

For certain connector manufacturers, the mass gain leads to decrease the connector cost and presents a non negligible interest. In the second phase, we optimize the sample volume with the constraints noted in Eqs. (3), (4) and (6). Fig.11 gives at 10 N, a contact resistance gain of 6.25 % and a volume gain of 12 %. In addition, the obtained Von-Mises was lower than the yield material stress (Table1). Fig.12 gives a comparison between the Von Mises stress and the mesh in the contact zone for the initial model and the optimized model. A slight modification of the mesh was observed between the initial and final design, the maximum Von Mises stress was located near the contact zone and it equals 313 MPa (Fig.12 (b)) for the optimized design which was less than
the value calculated for the initial design (357 MPa) (Fig.12 (a)).

Fig.14 : Contact resistance of the initial and optimized designs for spherical material contact C19210 (objective function is the volume)

Fig.15 : Mesh and Von Mises stress distribution in the contact zone (a) initial model (b) final optimized model

These results are interesting for the connector designers because the gain was triple: minimization of the volume, the contact resistance and the Von Mises stress.

5 Conclusion
Contact resistance and temperature evolution are studied for sphere/plane and cylindrical/plane electrical contact using high copper alloys under indentation tests. For the same conditions, spherical contact leads to lower electrical contact resistances than the ones obtained in the case of cylinder/plane contact. On the other hand, a higher electric current leads to a higher heating of the contact zone, whereas a higher indentation force leads to the opposite results.

A numerical simulation using a finite element modelling shows that when the roughness profile is taken into account, the obtained results are improved and approach the experimental curves. A numerical optimization procedure made it possible to obtain optimized shape for the minimal resistance or for the minimal volume when the samples are submitted to electrical, mechanical or geometrical constraints.

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References: